Generation of Axion-Like Couplings via Quantum Corrections in a Lorentz Violating Background

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Abstract

Light pseudoscalars, or axions like particles (ALPs), are much studied due to their potential relevance to the fields of particle physics, astrophysics and cosmology. The most relevant coupling of ALPs from the viewpoint of current experimental searches is to the photon: in this work, we study the generation of this coupling as an effect of quantum corrections, originated from the presence of a fermion field which feels an underlying Lorentz violating background. We show that this mechanism involves the calculation of a triangle graph, which is finite but ambiguous, so it might represent an interesting connection between a theoretical puzzle and an active field of experimental research. Most interestingly, we show that the axion-photon interaction generated by this mechanism turns out to be Lorentz invariant, thus mimicking the standard ALPs coupling to photon that is considered in the experiments. We comment on what kind of bounds in Lorentz violating parameters might be obtained from this connection. Finally, we argue that a similar mechanism can also generate Lorentz invariant coupling involving scalar particles and the photon, thus playing a possible role in the phenomenology of Higgs bosons.

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The search for light pseudoscalars have been an active field of experimental work. Such particles are usually taken as being pseudo-Nambu-Goldstone bosons, which arise from the breaking of global symmetries. The axion is a prominent example appearing from the breaking of a global chiral $U(1)$ symmetry and leading to a dynamical solution for the strong CP problem [1–3], being only the "invisible axion"-type models [4–7] actually phenomenologically viable. In addition, compactifications in string theory have also been shown to produce light pseudoscalars [8] (see also [9] and references therein).

More concretely, consider a pseudoscalar field ϕ coupled to a charged fermion field ψ according to the term $i\phi\overline{\psi}\gamma_5\psi$. Assuming that the fermionic field is heavy, it can be integrated out, and the low energy effective Lagrangian describing the pseudoscalars interacting with photons turns out to be

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m_\phi}{2}\phi^2 - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} , \tag{1}$$

where $g_{\phi\gamma}$ is a coupling constant with inverse of mass dimension, $F_{\mu\nu}$ is the electromagnetic field-strengh, and $\tilde{F}^{\mu\nu} = \varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$ its dual. In axion models there is a specific relation between m_ϕ and $g_{\phi\gamma}$, but generically, very light pseudoscalars having interaction as in Eq. (1) are denoted as axion-like-particles (ALPs).

Experiments for testing the effects of the interaction

$$\mathcal{L}_{\text{int}} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{\phi\gamma}\phi\vec{E}\cdot\vec{B} , \tag{2}$$

have been proposed and performed along the last decades [10–12]; combining these with astrophysical constraints from energy loss in stars [13], the interaction in Eq. (2) is now excluded in an impressive range of values $g_{\phi\gamma} \gtrsim 10^{-10}\text{GeV}^{-1}$ for a wide range of mass m_ϕ in the sub-eV scale [14]. Also, new proposals for searching ALPs whose couplings with photons could be directly tested up to $g_{\phi\gamma} \sim 10^{-11} - 10^{-12}\text{GeV}^{-1}$ are underway [15, 16].

Our main purpose in this work is to show that an interaction like Eq. (2) can be generated from a theory with a Lorentz violating background. More precisely, we will assume the existence of a massive fermionic field with Lorentz violating (LV) interactions of a specific form, and show that the resulting low energy effective Lagrangian contains Lorentz invariant interactions whose intensity are functions of LV parameters. In this way the experiments for searching ALPs would also be able to probe a specific setup of LV that we consider for the first time here.

Concerning theories which include LV, a framework for the incorporation of a possible LV within our current understanding of the elementary interactions has been used to provide an

environment for testing the validity of relativistic symmetry in different phenomena [17–19]. In essence, one incorporates in the Standard Model Lagrangian all possible covariant, renormalizable and gauge invariant terms that involve constant tensors. These are assumed to appear from a more fundamental theory at very high energy scales – via a spontaneous symmetry breaking that gives a nonvanishing vev for some tensorial field, for instance [20]. One example is the so-called Carrol-Field-Jackiw (CFJ) term $k_\mu \epsilon^{\mu\nu\rho\sigma} A_\nu \partial_\rho A_\sigma$ [21], which leads to modified propagation of light waves in vaccum and – since these effects are not seen in our current experiments – to strong bounds on the value of the Lorentz violating parameter k_μ. Such a term can be induced by quantum corrections, similarly to the mechanism described in the first paragraph, but starting from the Lorentz breaking coupling $b_\mu \overline{\psi} \gamma_5 \gamma^\mu \psi$, thus providing a connection between the b_μ and the coefficient k_μ; such connection between k_μ and b_μ would allow the translation of constraints from the photon sector to other sectors of the Lorentz violating extension of the Standard Model, strongly constraining these models.

Let us consider the following Lagrangian,

$$\mathcal{L} = \bar{\psi} \left[i\partial\!\!\!/ - m - \gamma^\mu (eA_\mu + gF_{\mu\nu} b^\nu) - \gamma_5 b\!\!\!/ \phi \right] \psi \,, \tag{3}$$

in which the electromagnetic field interacts minimally with a fermionic field, but also non-minimally via the Lorentz breaking interaction $gF_{\mu\nu} b^\nu \overline{\psi} \gamma^\mu \psi$. One should note that the coupling constants e and g have different mass dimensions. The pseudo-scalar field ϕ enters via the Lorentz-breaking Yukawa coupling[30]. Within this model, b_μ is the constant vector responsible for the Lorentz symmetry breaking. We shall not be interested in investigating the origin of the nonvanshing b_μ, but rather to see if from Eq. (3) we can generate the interaction in Eq. (2). Since it is natural to assume that b_μ is small, we do not introduce an independent coupling constant for the Yukawa term, because it could be reabsorbed by a redefinition of b_μ: it is enough to consider the constant g to characterize how differently the photon and the fermions interact with the Lorentz violating background.

The one-loop correction to the effective action of the gauge field A_μ can be expressed as usual in terms of a functional trace,

$$S_{\text{eff}}[b, A] = -i \, \text{Tr} \ln \left(i\partial\!\!\!/ - m - \gamma^\mu \tilde{A}_\mu - \gamma_5 b\!\!\!/ \phi \right) \,, \tag{4}$$

where

$$\tilde{A}_\mu = eA_\mu + gF_{\mu\nu} b^\nu . \tag{5}$$

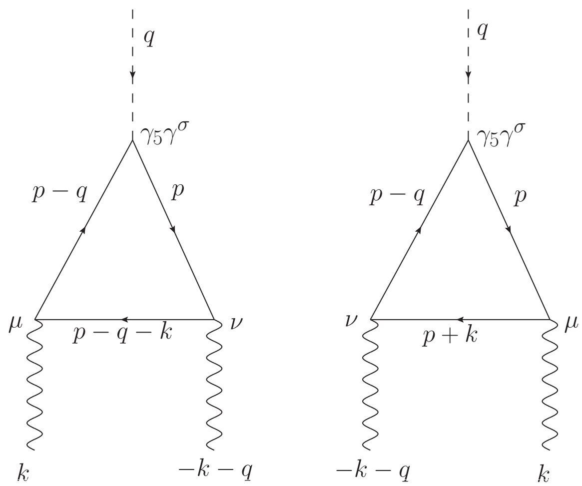

Figure 1: Triangle graphs corresponding to Eq. ((9)); the momenta associated with the external lines are momenta *entering* the corresponding line.

This effective action can be expanded in the following power series,

$$S_{\text{eff}}[b,A] = i\,\mathrm{Tr}\sum_{n=1}^{\infty}\frac{1}{n}\left[\frac{1}{i\partial\!\!\!/ - m}\,\left(\gamma^\mu\tilde{A}_\mu + \gamma_5 b\!\!\!/\phi\right)\right]^n . \tag{6}$$

We isolate in (6) the contributions of the second order in $\tilde{A}_\mu$ and first order in ϕ,

$$S_{\text{eff}}[b,A] \supset i\,\mathrm{Tr}\left[\frac{1}{i\partial\!\!\!/ - m}\gamma^\mu\tilde{A}_\mu\frac{1}{i\partial\!\!\!/ - m}\gamma^\nu\tilde{A}_\nu\frac{1}{i\partial\!\!\!/ - m}\gamma_5 b\!\!\!/\phi\right], \tag{7}$$

where the cyclic property of the trace have been used. Taking into account Eq. (5), after Fourier transform, one obtains

$$S_{\text{eff}}[b,A] \supset egb^\rho b_\sigma \int \frac{d^4k}{(2\pi)^4}\frac{d^4q}{(2\pi)^4}\,\tilde{\phi}\,(q)\,A_\mu\,(k)\,F_{\nu\rho}\,(-k-q)\,\Pi^{\mu\nu\sigma}\,(k,q)\ , \tag{8}$$

where the one-loop correction to the vacuum polarization reads

$$\begin{aligned}\Pi^{\mu\nu\sigma}\,(k,q)\ &= i\,\mathrm{tr}\int\frac{d^4p}{(2\pi)^4}\gamma^\mu S\,(p-k-q)\,\gamma^\nu S\,(p)\,\gamma_5\gamma^\sigma S\,(p-q)\\ &\quad + i\,\mathrm{tr}\int\frac{d^4p}{(2\pi)^4}\gamma^\nu S\,(p+k)\,\gamma^\mu S\,(p)\,\gamma_5\gamma^\sigma S\,(p-q)\ .\end{aligned} \tag{9}$$

Here, $S(p) = (p\!\!\!/ - m)^{-1}$ is the free Fermion propagator.

Eq. (9) corresponds to the sum of triangle graphs depicted in Fig. 1: if the external momenta q is set to zero, these graphs turn out to be rather similar to the ones considered in the perturbative generation of the CFJ term as studied, for example, in [22], with a difference of momentum routing that amounts to a shift in the integration momentum $p \to p-k$. Since these integrals are linearly divergent, such a shift would produce a *finite* shift in the result of the integrals, i.e.,

$$\Pi^{\mu\nu\sigma}\,(k,q)\big|_{q=0} = \tilde{\Pi}^{\mu\nu\sigma}\,(k) + C'\varepsilon^{\mu\nu\sigma\rho}k_\rho\,, \tag{10}$$

where C' is a finite constant, and $\tilde{\Pi}^{\mu\nu\sigma}(k)$ is the polarization tensor appearing in [22]. The Feynman integral involved in $\tilde{\Pi}^{\mu\nu\sigma}(k)$ turns out to be finite and ambiguous upon regularization, but also proportional to $\varepsilon^{\mu\nu\sigma\rho}k_\rho$. We can therefore conclude that

$$\Pi^{\mu\nu\sigma}(k,q)\big|_{q=0} = C\varepsilon^{\mu\nu\sigma\rho}k_\rho\,, \tag{11}$$

where the exact value of the *finite* coefficient C depends on the regularization scheme and the way the integral is manipulated (some of the "possible" values for C are quoted in [23]).

In summary, from Eqs. (9) and (11), we can state that

$$\Pi^{\mu\nu\sigma}(k,q) = C\epsilon^{\mu\nu\sigma\rho}k_\rho + q_\sigma\frac{\partial}{\partial q_\sigma}\,\Pi^{\mu\nu\sigma}(k,q)\big|_{q=0} + \text{finite terms}\,. \tag{12}$$

The first term in Eq. (12) is finite and ambiguous; the second one may be at the most logarithmically divergent, but we expect it to be finite due to its similarity with the box graph in standard QED. Thus the quantum corrections to the photon effective action in our theory are completely finite. We are not interested in evaluating the remaining terms of Eq. (12) at this moment: we focus on the first term since it will lead to the kind of ALP-photon interaction we are interested in. Without further comments on the value of the constant C at this point, one can go back to Eq. (8), substituting the result (12), thus obtaining

$$S_{\rm eff}[b,A] \supset C\,eg\,\phi\epsilon^{\rho\mu\nu\lambda}F_{\rho\mu}b_\lambda b^\kappa F_{\kappa\nu}\,. \tag{13}$$

To recognize in (13) an expression similar to (2), one has to note that

$$\epsilon^{\rho\mu\nu\lambda}F_{\rho\mu}b_\lambda b^\kappa F_{\kappa\nu} = 2b^2\vec{E}\cdot\vec{B}\,, \tag{14}$$

therefore

$$S_{\rm eff}[b,A] \supset 2C\,egb^2\,\phi\vec{E}\cdot\vec{B}\,. \tag{15}$$

This is the main result of this paper. We obtain with the mechanism described in the previous paragraphs a term of the same form as Eq. (2), which is the most relevant interaction involving the pseudo-scalar, from the point of view of current experimental searches.

It is surprising to notice that even if the model started with explicit Lorentz violation, the generated interaction depends only on the scalar $b^2 = b^\mu b_\mu$. That means the underlying LV background involving the vector b_μ that we considered generated a *Lorentz invariant* interaction, which mimics precisely the effects of the ALPs interactions studied in the Lorentz preserving context. We conclude that, whenever the kind of LV that we considered as the initial input for our

calculations turns out to happen in nature, the *effective* ALP-photon coupling that are measured by experiments is actually

$$G^{(eff)}_{a\gamma\gamma} aF_{\mu\nu}\tilde{F}^{\mu\nu} = \left(G^{(LI)}_{a\gamma\gamma} + 2C\, egb^2\right) aF_{\mu\nu}\tilde{F}^{\mu\nu} \,, \tag{16}$$

where $G^{(LI)}_{a\gamma\gamma}$ represents the contribution generated by other – Lorentz invariant – mechanisms (such as the Peccei-Quinn mechanism for solving the strong CP problem). At the very least, the observation in Eq. (16) affects the relation between the axion mass and couplings appearing in standard scenarios. One might even say that Lorentz violation could represent an alternative mechanism to generate such couplings, that is, even if $G^{(LI)}_{a\gamma\gamma} = 0$, one could have the essential signals of the presence of an ALP induced only via LV.

Another appealing property of the mechanism presented here is that the entire construction depends on the presence of a fermion ψ which feels the underlying LV of the specific form we proposed. This fermion could be very massive, which justifies integrating out its degrees of freedom, with the remnant of its presence given by effective interactions such as (15). Also, our conclusions are independent of the mass of the ALP, which could be as small as necessary to fit into experimental constraints.

The appearance of the ambiguous constant C in (15) brings into question the technical puzzle involved in its calculation. Assuming, for the sake of the argument, $C \sim 1$, one roughly obtains from (15) and (2) the experimental constraint

$$egb^2 \lesssim 10^{-10}\text{GeV}^{-1} \,. \tag{17}$$

We are unaware of independent experimental constraints on the Lorentz violating couplings $gb^\nu F_{\mu\nu}\bar{\psi}\gamma^\mu\psi$ and $\phi\bar{\psi}\gamma_5\not{b}\psi$, but if one of these could be found, we could put an experimental constraint on the other one. Notice however that (15) is of second order in b_μ, so we might not be able to put very stringent bounds on g based on Eq. (17). This is a question that deserves further study since it connects the ambiguous constant C with an experimentally observable quantity, namely the effective coupling in Eq. (15).

In summary, the connection between Lorentz violation and the phenomenology of axion-like particles can have very interesting consequences both for the searches of possible violations of standard spacetime symmetries, and for the search of the elusive light pseudoscalars that could solve many theoretical puzzles in our current understanding of the universe.

To finish, one may wonder whether other relevant Lorentz invariant operators could be induced

by and underlying LV dynamics. The answer actually is yes: if, for example, one starts with

$$\mathcal{L} = \bar{\psi}\left[i\partial\!\!\!/ - m - \gamma^{\mu}\left(eA_{\mu} + g' d^{\nu}\epsilon_{\mu\nu\lambda\rho}F^{\lambda\rho}\right) - \gamma_5 d\!\!\!/ h\right]\psi\,, \tag{18}$$

instead of Eq. (5), where now d_μ is a pseudovector, so that h is a scalar field, by repeating the steps described in the previous paragraphs one would arrive at

$$S_{\rm eff}[b,A] \supset 2Cg' e\,\epsilon^{\rho\mu\nu\lambda} d_\lambda \epsilon_{\nu\kappa\sigma\tau} d^\kappa\, hF_{\rho\mu}F^{\sigma\tau}\,. \tag{19}$$

In this way one generates scalar couplings to the photon of the general form

$$\mathcal{L}_{h\gamma} = c_1 h\left(d^\mu F_{\mu\nu}\right)^2 + c_2 d^2 h F^{\mu\nu}F_{\mu\nu}\,. \tag{20}$$

The first term is sensitive to the direction of the Lorentz breaking vector d_μ; this can be made explicit by rewriting it as

$$c_1 h\left[-\left(d^0\right)^2\vec{E}^2 + \left(2d^0\right)\vec{d}\cdot\left(\vec{E}\times\vec{B}\right) + \left(\vec{E}\cdot\vec{d}\right)^2 + \vec{d}\cdot\left[\vec{B}\times\left(\vec{B}\times\vec{d}\right)\right]\right]\,. \tag{21}$$

From this interaction, a typically Lorentz violating phenomenology could be studied, namely, the dependence of physical measurements on the direction of the vector d_μ, which by assumption is fixed in some preferred cosmological Lorentz frame.

The second term in Eq. (20), however, depend only on the scalar d^2, and it is identical in form to the effective coupling in the Standard Model that is responsible for the diphoton Higgs boson decay. This decay was one of the main channels for the observation of the resonance at 126 GeV recently discovered at the LHC [24, 25]. We may speculate, therefore, that LV could play a relevant role in possible deviations from the predictions of the Stardard Model for this particular process.

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